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Recent DØ Results on the Top Quark

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Recent results on top quark physics with the DØ experiment in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV for an integrated luminosity of 125 pb^{-1} are reported. The direct measurement of the top quark mass uses single lepton events, giving the result $m_{top} = 173.3 \pm 5.6(\text{stat.}) \pm 6.2(\text{syst.}) \text{ GeV}/c^2$. The measurement of the $t\bar{t}$ production cross section includes analyses from 8 top decay channels: dilepton ($t\bar{t} \rightarrow e\mu, ee$, and $\mu\mu$), electron and neutrino ($t\bar{t} \rightarrow e\nu$), and single leptons ($t\bar{t} \rightarrow e + \text{jets}$ and $t\bar{t} \rightarrow \mu + \text{jets}$) with and without b tagging. We measure the $t\bar{t}$ production cross section to be $5.5 \pm 1.8 \text{ pb}$ at $m_{top} = 173.3 \text{ GeV}/c^2$.

1. Introduction

Since the top quark was discovered [1,2] by the DØ and CDF experiments at the Fermilab Tevatron collider in 1995, much of the current effort has been focused on measuring the $t\bar{t}$ production cross section and the top quark mass.

In the Tevatron $\bar{p}p$ collider at a center of mass energy of 1.8 TeV top quarks are predominantly produced in pairs through $q\bar{q}$ annihilation ($\sim 90\%$) or gluon fusion ($\sim 10\%$). According to the standard model a top quark decays almost 100% of the time into a W and a b quark. Each W boson decays either into a charged lepton and a neutrino or into a pair of quarks. Our analysis channels are classified on the basis of the W boson decay. The cleanest channel is dilepton channel, $t\bar{t} \rightarrow 2 \text{ leptons} + 2 \text{ neutrinos} + 2 \text{ jets}$, where both W bosons decay into leptons. There is a branching ratio of $\frac{4}{81}$ for $t\bar{t}$ decays into $e\mu$, ee , and $\mu\mu$ channels. The single lepton decay channel, where one W boson decays leptonically and other W boson decays hadronically, has a branching ratio of $\frac{24}{81}$, but it has a sizable background from W +jets production.

This paper reports the recent DØ results on the $t\bar{t}$ production cross section using the dilepton and single lepton decay channels, and on the direct measurement of the top quark mass using the single lepton channel.

The results reported in this paper use the entire

data sample, which has an integrated luminosity of about 125 pb^{-1} , and which was collected during the 1992-1996 collider run. Since our report on the discovery of the top quark [1], our data sample has doubled. DØ has optimized the analysis to maximize the expected precision of the $t\bar{t}$ production cross section measurement and improved the techniques on the measurement of the top quark mass.

2. Measurement of $t\bar{t}$ Production Cross Section

The triggers and the particle identification algorithms used in these analyses are described in detail in DØ publications [1,3].

2.1. Dilepton Decay Channels

The signature of $t\bar{t}$ events in the dilepton decay channels is two high p_T isolated leptons, two or more jets and large missing E_T (\cancel{E}_T) due to the presence of the two neutrinos.

The offline event selection requires that the isolated electrons have $E_T > 20 \text{ GeV}$ with $|\eta| < 2.5$ and that the isolated muons have $p_T > 15 \text{ GeV}$ with $|\eta| < 1.7$. At least two jets are required to be reconstructed with a transverse energy above 20 GeV with $|\eta| < 2.5$. All jets are reconstructed using a cone algorithm with radius 0.5 in η - ϕ space. The \cancel{E}_T is required to be above 25 GeV for the ee channel and to be above 20 GeV for

the $e\mu$ channel. In addition, we apply a cut on a variable H_T , which is defined as the sum of the E_T 's of all the jets in the event plus the leading electron E_T . We expect a higher H_T for $t\bar{t}$ events than for background events. We require the H_T to be above 120 GeV for the ee and $e\mu$ channels, and to be above 100 GeV for the $\mu\mu$ channel.

The background in these channels is mainly from Z^0 decays, Drell-Yan, vector boson pair events and events with misidentified leptons.

Five events passed the above selection criteria for the dilepton decay channel, with estimated background 1.4 ± 0.4 events (see Table 1).

2.2. Single Lepton Decay Channels

The signature of $t\bar{t}$ events in the single lepton channels is a high p_T isolated lepton, large \cancel{E}_T and high jet multiplicity. We divide the single lepton channel analysis into two complementary and orthogonal analyses: an event shape analysis and a b tagging analysis. The main sources of background in the single lepton channels are W +jet events with high jet multiplicity and multijet QCD events with fake leptons and \cancel{E}_T due to mismeasurement.

In the event shape analysis the $t\bar{t} \rightarrow e + \text{jets}$ and $t\bar{t} \rightarrow \mu + \text{jets}$ events are selected by use of topological and kinematic cuts. The offline event selection requires one isolated lepton with $E_T > 20$ GeV with $|\eta_e| < 2.0$ or $|\eta_\mu| < 1.7$ and at least 4 jets with $E_T > 15$ GeV with $|\eta_{jet}| < 2.0$. The \cancel{E}_T requirement is 25 GeV for the $e + \text{jets}$ channel and 20 GeV for the $\mu + \text{jets}$ channel. The event shape analysis uses the global event variable aplanarity, \mathcal{A} , which is defined as $\frac{3}{2}$ of the smallest normalized eigenvalue of the 3-momentum tensor of the W boson and jet momenta in the laboratory frame. Background events typically have smaller \mathcal{A} than signal events. Another variable used in the event shape analysis is H_T , which is defined as the sum of the E_T 's of all the jets in the event. $t\bar{t}$ events are expected to have a higher H_T than W +jets events. In addition we also require the total leptonic E_T , E_T^L , which is defined as the sum of the charged lepton E_T and \cancel{E}_T , to be above 60 GeV to reject the multijet QCD background. We require the pseudorapidity η_W of the W boson that decays leptonically to have

$|\eta_W| < 2.0$ to obtain better agreement between background control samples from data and the W +jets Monte Carlo (MC) samples [4].

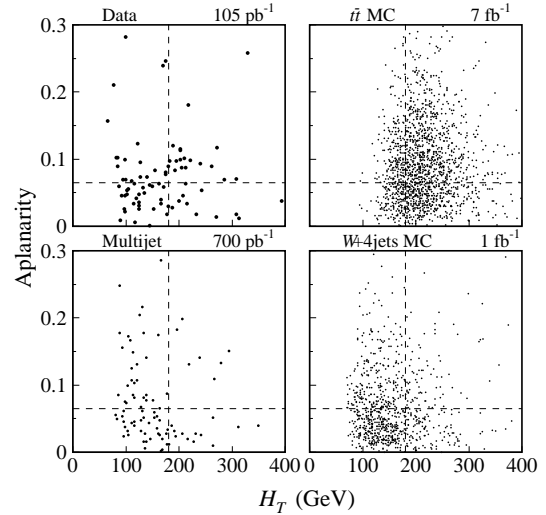


Figure 1. Aplanarity vs H_T for single lepton data, $t\bar{t}$ MC events, multijet background and W +4 jets MC background. The dashed lines indicate the cuts.

Figure 1 shows scatter plots of \mathcal{A} vs H_T for $D\bar{D}$ single lepton data, $t\bar{t}$ ($m_{top} = 170$ GeV/ c^2) MC events, and the two background sources: multijet background and $W + 4$ jets VECBOS [5] MC events. Based on our optimization procedure using $t\bar{t}$ MC events, we define the region $\mathcal{A} > 0.065$ and $H_T > 180$ GeV as the signal region.

$W + \text{jets}$ background events and the multijet QCD events are the main source of backgrounds in the lepton + jets channel. Since the number of $W + \text{jets}$ events is expected to decrease exponentially as a function of the jet multiplicity [6], by fitting the number of $W + \text{jets}$ events at the lower jet multiplicity and extrapolating it to high jet multiplicities, we can estimate the number of $W + \text{jets}$ background events in the data sample. We estimate the QCD background from the data itself using the measured jet misidentification probability.

Nineteen events survived all the cuts in the event shape analysis for the single lepton channel, with estimated background 8.7 ± 1.7 events

(see Table 1).

The other analysis in the single lepton channel is the b tagging analysis. The background for the single lepton channel can be significantly reduced by requiring that one of the jets is tagged as a b -jet. We tag b 's by detecting a muon in a jet. About 20% of $t\bar{t}$ events have a detectable μ in a jet compared to only about 2% of the $W + (\geq)3$ jets background events. A tag muon is required to have $p_T^\mu > 4$ GeV and the distance ΔR between the muon and a jet in the ϕ - η plane must be less than 0.5.

The offline event selection in the b tagging analysis requires one isolated lepton with $E_T > 20$ GeV with $|\eta_e| < 2.0$ or $|\eta_\mu| < 1.7$, $\cancel{E}_T > 20$ GeV, and 3 or more jets with $E_T > 20$ GeV with $|\eta_{jet}| < 2.0$. Since we require a tag muon in the event, we use looser cuts on aplanarity and H_T compared to the event shape analysis, $\mathcal{A} > 0.040$ and $H_T > 110$ GeV. Figure 2 shows the distribution of the jet multiplicity for background events and for single lepton data before the \mathcal{A} and H_T cuts. The data agrees with the number of events from $W +$ jets and QCD processes in the low jet multiplicity region. For the high multiplicity bin we can see a clear excess above background even without the \mathcal{A} and H_T cuts.

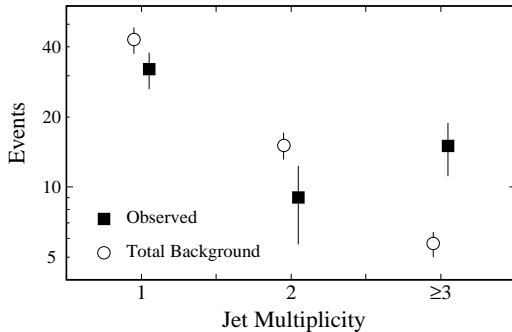


Figure 2. Jet multiplicity distribution for single lepton b -tag events (before applying \mathcal{A} and H_T cuts), compared to background estimates.

The main background in the b tagging analysis is also W +jets production. The background is estimated by applying the muon tag rate, which is

determined by the fraction of jets tagged in multijet events, to the jets in the background sample after all other cuts described above are applied.

Eleven events passed the above selection criteria in the b tagging analysis of the single lepton channel, with estimated background 2.4 ± 0.5 events (see Table 1).

2.3. $e\nu$ Decay Channel

In order to identify $t\bar{t}$ events in which neutrinos from both W decays carry much of the transverse momentum, we perform an $e\nu$ decay channel analysis. This analysis is mainly focused on selecting those $t\bar{t}$ events with an electron in the final state that fail the event selection criteria for the ee , $e\mu$ and e +jets decay channels. The signature of the $t\bar{t}$ events in the $e\nu$ decay channel is one high p_T isolated electron, two or more jets and very large \cancel{E}_T which together with the electron, forms a transverse mass much higher than the W mass.

The event selection requires events with an isolated electron with $E_T > 20$ GeV with $|\eta_e| < 1.1$ and at least two jets with $E_T > 30$ GeV with $|\eta_{jet}| < 2.0$. We require that the \cancel{E}_T is above 50 GeV and the transverse mass of the \cancel{E}_T and the electron is above 115 GeV. The dominant background in this channel is W +jets production, W pair production and a misidentified electron with \cancel{E}_T in QCD multijet events.

Four events survived the selection criteria for the $e\nu$ decay channel, with estimated background 1.2 ± 0.4 events (see Table 1).

2.4. $t\bar{t}$ Production Cross Section

Table 1 shows the number of observed events for all eight decay channels, the estimated number of background events, and the expected number of $t\bar{t}$ events for three top mass hypotheses ($t\bar{t}$ production cross sections using ref. [7]).

The top production cross section is calculated using the formula $\sigma_{t\bar{t}} = \frac{\sum_{i=1}^8 (N_i - B_i)}{\sum_{i=1}^8 \epsilon_i \mathcal{B}_i L_i}$ where N_i is the number of observed events, B_i is the expected background, ϵ_i is the detection efficiency for top, \mathcal{B}_i is the branching ratio and L_i is integrated luminosity for decay channel i .

Figure 3 shows the $D\bar{D}$ $t\bar{t}$ cross section as a

Table 1
Event yields

channel	events observed	background	expected signal m_t (GeV/c ²)		
			150	170	190
ee	1	0.5 ± 0.1	1.9 ± 0.3	1.2 ± 0.2	0.8 ± 0.1
$e\mu$	3	0.2 ± 0.2	3.2 ± 0.7	2.2 ± 0.5	1.4 ± 0.3
$\mu\mu$	1	0.7 ± 0.3	0.8 ± 0.1	0.6 ± 0.1	0.4 ± 0.1
e +jets(event shape)	9	4.5 ± 0.9	10.8 ± 3.6	8.6 ± 1.6	5.5 ± 0.7
μ +jets(event shape)	10	4.2 ± 1.0	7.5 ± 2.9	5.5 ± 1.7	3.7 ± 0.9
e +jets(b -tag)	5	1.1 ± 0.4	5.9 ± 1.0	3.6 ± 0.6	2.4 ± 0.4
μ +jets(b -tag)	6	1.4 ± 0.2	3.2 ± 0.8	2.3 ± 0.5	1.4 ± 0.3
$e\nu$	4	1.2 ± 0.4	2.5 ± 0.8	1.7 ± 0.5	1.1 ± 0.3
total	39	13.7 ± 2.2	35.9 ± 8.8	25.7 ± 4.6	16.6 ± 2.4

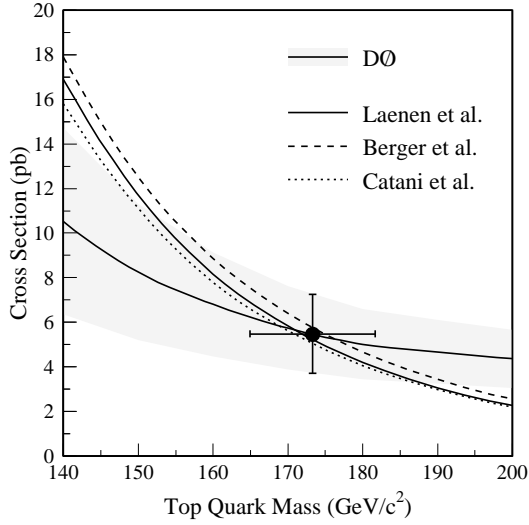


Figure 3. Top cross section vs top quark mass

function of top quark mass compared with theoretical predictions. The band on the DØ measured cross section curve indicates the error including the statistical and systematic errors. We measure the $t\bar{t}$ production cross section to be $\sigma_{t\bar{t}} = 5.5 \pm 1.4(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.6(\text{gen.})$ pb at our measured top quark mass of $m_{top} = 173.3$ GeV/c² (see section 3) in good agreement with the standard model predictions.

3. Measurement of the Top Quark Mass

The direct measurement of top quark mass using single lepton plus jets events is reported here.

3.1. Event Selection

The initial event selection for the top quark mass measurement analysis is similar to that used in the cross section analysis for the single lepton channel, but without \mathcal{A} and H_T cuts. We require one isolated lepton, e or μ , with $E_T > 20$ GeV and $|\eta_e| < 2.0$ or $|\eta_\mu| < 1.7$, and $\cancel{E}_T > 20$ GeV. Only the events with four or more jets having $E_T > 15$ GeV with $|\eta_{jet}| < 2.0$ are used. In untagged events, to suppress background we require $E_T^L > 60$ GeV and $|\eta_W| < 2$ for the $W \rightarrow \ell\nu$.

Ninety events passed the event selection requirements. Among them seven events are b -tagged events.

3.2. Fitting Algorithm

For each event passing the above selection cuts, we make a two constraint (2C) kinematic fit [8] to the $t\bar{t} \rightarrow \ell + \text{jets}$ hypothesis by minimizing a $\chi^2 = (v - v^*)^T G (v - v^*)$, where $v(v^*)$ is the vector of the measured (fit) variables and G^{-1} is its error matrix [9]. Both reconstructed W masses are constrained to equal the W mass and we assume both t and \bar{t} quarks have the same fit mass, m_{fit} . Kinematic fits were performed on all permutations of the jet assignments of the four highest E_T jets, with the provision that muon-tagged jets were always assigned to a b -quark in the fit. Each

fit yields a fitted mass value, m_{fit} and a χ^2 . The fit with the lowest χ^2 is chosen to describe the event. Only the events with $\chi^2 < 10$ are used in the top quark mass determination. 77 events passed the χ^2 cut and among them five events are b -tagged events. Although m_{fit} is strongly correlated with the top quark mass, m_{top} , m_{fit} is not the same as m_{top} , because of permutation ambiguities.

3.3. Mass and Error Determination

To further separate the signal and background events we use variables that can provide good separation between $t\bar{t}$ and background events without much correlation to the fitted mass. The following four variables are chosen to compute the top quark likelihood discriminant (D):

- E_T .
- \mathcal{A} .
- $H_{T2}/\Sigma|p_Z|$, where H_{T2} is the H_T without the E_T of the leading jet.
- $\min(\Delta R_{jj})E_T^{\text{min}}/(E_T^L)$, where (ΔR_{jj}) is the minimum ΔR between all pairs of the jets and E_T^{min} is the smaller jet E_T from the minimum ΔR pair.

$D\phi$ uses two discriminants [9]. One is the D_{LB} (low bias) method, in which we parametrize $\mathcal{L}_i(x_i) \equiv s_i(x_i)/b_i(x_i)$, where s_i and b_i are the top signal and background densities in each variable, integrating over the others. We then form the log likelihood $\ln \mathcal{L} \equiv \sum_i \omega_i \ln \mathcal{L}_i$, where the weights ω_i are adjusted slightly away from unity to nullify the average correlation (“bias”) of \mathcal{L} with m_{fit} . For each event we set $D_{LB} = \mathcal{L}/(1 + \mathcal{L})$. The data are then divided into two bins: a low signal-to-noise bin and a high signal-to-noise bin, according to whether the LB cut is passed. The LB cut is passed if either $D_{LB} > 0.43$ and $H_{T2} > 90$ GeV, or if a b tag exists in the event. Another method uses a neural network [10] with the same four variables as input, five hidden nodes, and one node with output D_{NN} . We divide the data into ten bins in D_{NN} . Figure 4 shows the distribution of the discriminants D_{LB} and D_{NN} for

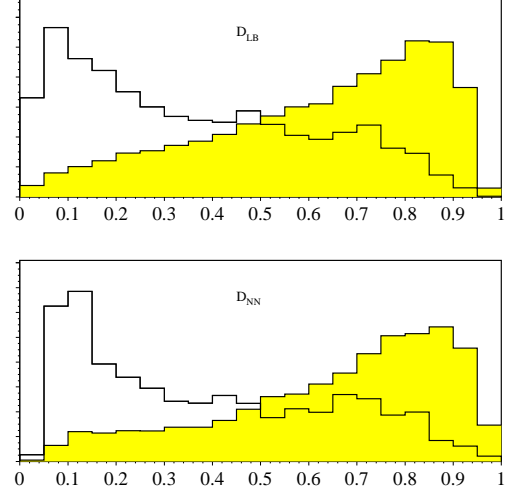


Figure 4. Distribution of discriminants, D_{LB} and D_{NN} for 175 GeV/c² top MC (shaded histogram) and for background (unshaded histogram).

signal and background. They indicate that either discriminant provides good discrimination.

Since the selected event sample contains both $t\bar{t}$ and background events, we make a two dimensional likelihood fit of the event sample to the sum of the expected $t\bar{t}$ signal plus background in the m_{fit} vs. D plane. We make an independent likelihood fit for each top quark mass hypothesis. We use the HERWIG [11] MC to simulate $t\bar{t}$ events. We estimate background using a combination of W +jets events from the VECBOS [5] MC and fake lepton events obtained directly from $D\phi$ data.

Figures 5 (a) and (b) show the distributions of m_{fit} for data (a) passing and (b) failing the LB cut. The histograms are data, the dots are the predicted mixture of signal plus background, and triangles are background. Figure 5 (c) shows the log of the fit likelihood L vs. true top quark mass m_{top} for both the LB and NN fits. The curves are quadratic fits to the lowest point and its 8 nearest neighbor points. The minimum position of each curve yields the measured top quark mass. The width of the curve at 0.5 above the minimum determines the statistical error of the measurement. The LB fit yields $m_{\text{top}} = 174.0 \pm 5.6$ (stat.) GeV/c². The NN fit

yields $m_{top} = 171.3 \pm 6.0$ (stat.) GeV/c^2 .

There are several sources of systematic error [9]. The major uncertainties are from the jet energy scale and the MC modelling of QCD effects. We assign a jet energy scale error of $\pm(2.5\% + 0.5 \text{ GeV})$ based on a detailed study of γ +jet events in data and MC, particularly focused on the dependence of the E_T balance upon η of the jet, and checked by the E_T balance in Z +jet events. This leads to an error on m_{top} of $\pm 4.0 \text{ GeV}/c^2$. The uncertainties in the MC modelling of QCD effects are estimated by substituting the ISAJET MC generator [12] for HERWIG, independently for top MC and for VECBOS fragmentation, and by changing the VECBOS QCD scale from jet $\langle p_T \rangle^2$ to M_W^2 . The resulting systematic error due to the generator is $\pm 4.1 \text{ GeV}/c^2$. Other effects, including calorimeter noise, multiple $p\bar{p}$ interactions, and differences in fits to $\ln L$, contribute $\pm 2.2 \text{ GeV}/c^2$. All systematic errors sum in quadrature to $\pm 6.2 \text{ GeV}/c^2$.

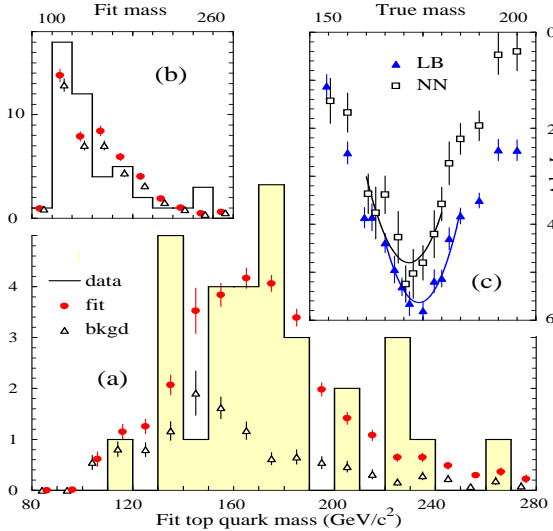


Figure 5. (a-b) Fit top quark mass distribution for events (a) passing or (b) failing the LB cut. (c) Log of likelihood L vs. true top quark mass m_{top} for both the LB and NN fits.

Combining m_{top} from both methods, LB and NN, we determine the top quark mass to be $m_{top} = 173.3 \pm 5.6$ (stat) ± 6.2 (syst) GeV/c^2 ,

allowing for the $(88 \pm 4)\%$ correlation between two methods.

3.4. Conclusions

DØ has measured the $t\bar{t}$ production cross section using the entire data sample from the 1992-1996 running period with an integrated luminosity of 125 pb^{-1} . In the cross section analysis thirty nine events were observed in eight different decay channels. The estimated background is 13.7 ± 2.2 events. The $t\bar{t}$ production cross section is measured to be $5.5 \pm 1.8 \text{ pb}^{-1}$ at $m_{top} = 173.3 \text{ GeV}/c^2$. DØ has made a direct measurement of the top quark mass from single lepton plus jets events. The top quark mass is determined to be $m_{top} = 173.3 \pm 8.4 \text{ GeV}/c^2$.

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